

THE EFFECT OF SUPERNOVA ASYMMETRY ON COALESCENCE RATES OF BINARY NEUTRON STARS

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We study the effect of the kick velocity – neutron star spin alignment observed in young radio pulsars on the coalescence rate of binary neutron stars. The effect is shown to be especially strong for large kick amplitudes and tight alignments, reducing the galactic rate of binary neutron star coalescences up to an order of magnitude with respect to the rates calculated for random kicks. The spin-kick correlation also leads to much narrower NS spin-orbit misalignments compared to random kicks.

1 Introduction

Kick velocity imparted to a newborn neutron star is known to be an important phenomenological parameter of core collapse supernovae. The origin of the kicks remains unclear (see, for example, ¹ and references therein). Recently, new important observational results appeared suggesting possible NS spin-kick alignment. Tight spin-kick alignment follows from measurements of radio pulsar polarization ², as well as from X-ray observations of pulsar wind nebulae around young pulsars ^{3,4}. Implications of these observations to the formation of double pulsars were discussed by Wang et al. ⁵. Here we explore the effect of NS spin – kick correlation on the formation and galactic coalescence rate of double neutron stars (DNS) which are primary targets for modern gravitational wave detectors. We show that the tighter alignment, the smaller is the DNS merging rate with respect to models with random kick orientation. The effect is especially important for large kick amplitudes (~ 400 km/s).

2 Effect on the binary neutron star coalescence rates

The effect of NS kick velocity on merging rates of compact binaries was studied earlier (e.g. ⁶). The observed tight NS spin – kick alignment may have important implications to the formation and evolution of binary compact stars (see especially earlier paper by Kalogera ⁷). Let us consider the standard evolutionary scenario leading to formation of binary NS from a massive binary system (see ⁸ for discussion and references) focusing on the effect of the NS kick velocity. We shall assume that the kick velocity vector is confined within a cone which is coaxial with the progenitor's rotation axis and characterized by angle $\theta < \pi/2$. We shall consider only central kicks thus ignoring theoretically feasible off-center kicks affecting the NS spin ^{9,10}. The value of the kick velocity is assumed to obey the Maxwellian distribution $f(v) \sim v^2 \exp(-(v/v_0)^2)$, as suggested by pulsar proper motion measurements ¹¹. The velocity v_0 varied from 0 to 400 km/s.

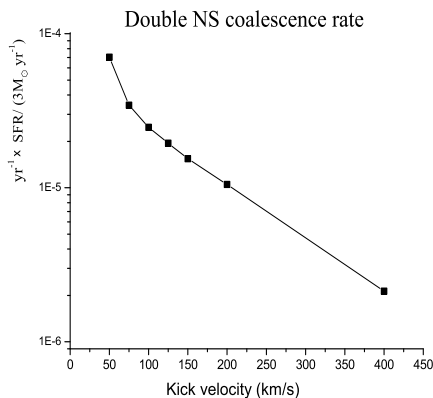


Figure 1: Galactic coalescence rate of DNS vs. kick parameter v_0 (random kicks). An almost exponential decay with v_0 is seen for $v_0 > 100$ km/s

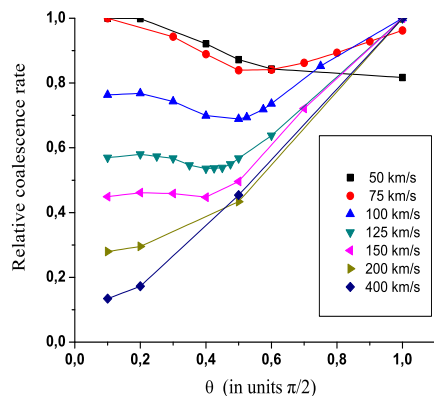


Figure 2: Relative change of DNS merging rate for NS spin-kick correlation

The rotational axes of both components are assumed to be aligned with the orbital angular momentum before the primary collapses to form first NS. The SN explosion is treated in a standard way as instantaneous loss of mass of the exploding star. The effect of the kick on the post-explosion binary orbital parameters is treated from the point of view of energy-momentum conservation in two point-mass body problem (see e.g. in ^{7,12}). The first SN explosion most likely occurs when the binary orbit is circular (unless the initial binary is very wide so that tidal circularization is ineffective), while the second explosion can happen before the orbit has been tidally circularized; in the latter case we choose the position of the star in the orbit distributed according to Kepler's 2d law.

We use the population synthesis method to calculate the expected coalescence rate of DNS (see ^{6,8} and references therein). The standard assumptions about binary evolution have been made: Salpeter's mass function for the primary's mass, $f(M_1) \sim M^{-2.35}$, flat initial mass ratio ($q = M_2/M_1 < 1$) distribution $f(q) = \text{const}$, initial semi-major axes distribution in the form $d \log a = \text{const}$. The common envelope phase is treated in the standard way⁸ with the efficiency $\alpha_{CE} = 0.5$. The calculations were normalized to the galactic star formation rate $3M_\odot$ per year, with binary fraction 50%. We also have carefully taken into account rotational evolution of magnetized compact stars, as described in ^{13,14}, assuming no magnetic field decay. The galactic DNS merging rate is shown in Fig. 1 as a function of the kick parameter v_0 and assuming random central kicks. Note an almost exponential decay of the rate with v_0 for $v_0 > 100$ km/s. Fig. 2 shows the relative change in the DNS merging rate when we allow for NS spin-kick alignment with different values of the confinement angle θ . It is seen that tight alignment generally reduces the DNS merging rate, with the effect being especially strong for large kick velocity amplitudes. Such a reducing relative to calculations with random kicks is in fact expected, because the NS spin – kick correlation excludes kicks in the orbital plane which, if directed opposite to the orbital velocity, can additionally bind the post-explosion binary system.

3 Neutron star spin – orbit misalignment

There is another observational consequence of the kick in DNS systems: NS spin – orbit misalignment, which can be tested by geodetic precession measurements in binary pulsars¹⁵. Such a misalignment is potentially very interesting for GW studies¹⁶. After SN explosion in a binary system, additional kick imparted to newborn NS results, in general, in a misalignment between the new orbital angular momentum and the NS (and the secondary component's) spin

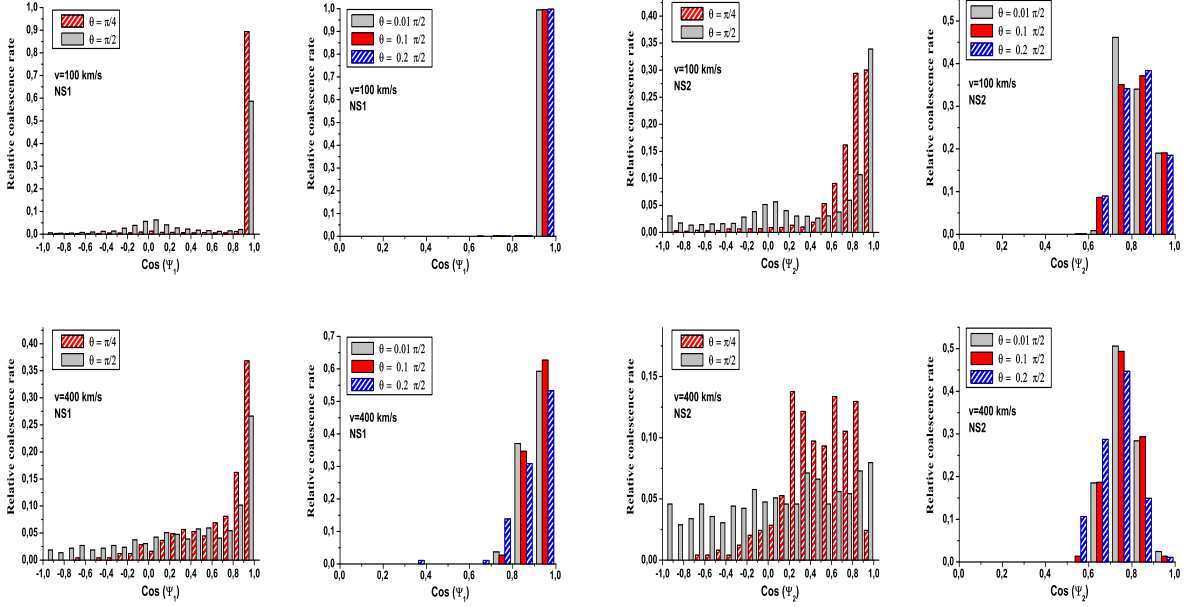


Figure 3: NS spin-orbit misalignment $\cos \Psi$ in coalescing DNS for $v_0 = 100$ km/s (upper row) and 400 km/s (bottom row) and different NS spin-kick alignment angles θ_0 . NS1: spin aligned with orbit before SN explosion; NS2: spin aligned with original binary's orbital angular momentum

vector characterized by angle Ψ_1 . After the second SN explosion in the system, there are several possibilities for the NS spin-orbit misalignment.

1) In sufficiently wide binaries, when tidal interactions between the components are inefficient, the orientation of the NS1 spin and the secondary's spin vector may remain unchanged until the second SN explosion, after which the orbital angular momentum vector changes again due to NS2 kick. So in this case we would expect two coaxial NS with spins misaligned by angle Ψ_2 with orbital angular momentum. However, such binaries, unless very eccentric, may be too wide to coalesce over the Hubble time.

2) In close binaries, tidal interactions tend to rapidly align angular momentum vector of the normal star with the orbital angular momentum. To spin-up the NS rotation up to observed ms periods (in binary ms pulsars), a modest amount of matter ($\sim 0.1M_\odot$) should be accreted by NS. This amount is sufficient to align the NS rotation with the orbital angular momentum. So if NS1 accretes matter before the second SN explosion, both NS1 and the secondary component's spins are most likely aligned with orbital angular momentum (see discussion in ⁵). Note that the NS1 spin tends to align with the orbital angular momentum even if NS1 does not accrete matter but spins-down by the propeller mechanism before the second SN explosion, since in that case very strong currents must flow through its polar cap and the alignment torques is as strong as during accretion. So the NS1 remains misaligned prior to the second SN explosion only in rare cases where the secondary collapses shortly after the first SN in the binary. If both NS1 and secondary were aligned with orbital angular momentum prior to the second SN explosion, both neutron stars will be equally misaligned with orbital angular momentum, $\Psi_1 = \Psi_2$.

In our population synthesis simulations we take into account the discussed spin alignment effects. In Fig. 3 we show the calculated distribution between the NS1 and NS2 spins and orbital angular momentum in coalescing DNS systems (angles Ψ_1 and Ψ_2 , respectively) assuming spin-orbit alignment (angle Ψ_1) and conservation of the secondary's angular momentum (angle Ψ_2). Clearly, the real distribution must be intermediate between the two, depending on the degree of misalignment of the secondary's angular momentum prior to the collapse. It is seen that the

Table 1: Mean NS spin-orbit misalignment Ψ (in units $\pi/2$)

Kick v_0 (km/s)	NS1 (Ψ_1)					NS2 (Ψ_2)				
	Kick confinement angle θ (in units $\pi/2$)									
	0.01	0.1	0.2	0.5	1.0	0.01	0.1	0.2	0.5	1.0
50	0.061	0.060	0.059	0.073	0.212	0.307	0.310	0.316	0.308	0.345
100	0.110	0.110	0.109	0.186	0.444	0.378	0.381	0.381	0.423	0.633
200	0.192	0.195	0.207	0.337	0.535	0.417	0.419	0.442	0.575	0.813
400	0.257	0.262	0.291	0.451	0.670	0.442	0.447	0.481	0.670	0.909

misalignment angles can be very different (and even with negative cosines) for random or loosely constrained ($\theta \sim \pi/2$) kicks, while tight spin-kick alignment ($\theta \ll \pi/2$) results in much narrow distributions (see also ⁷). The mean misalignment angles Ψ are presented in Table 1.

4 Conclusions

We have shown that the spin-velocity correlation observed in radio pulsars, suggesting NS spin-kick velocity alignment, may have very important implications to GW studies. First, the tight alignment reduces the galactic rate of double neutron star coalescences (especially for large kicks 300-400 km/s – up to ten times) relative to models with random kicks. Second, the spin-kick correlation results in specific distribution of NS spin – orbit misalignments, which can be tested by analysing GW signals from DNS mergings.

Acknowledgments

KAP acknowledges the financial support from the Meeting Organizers and RFBR grant 07-02-08065z.

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